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JPL MICRO-THRUST PROPULSION ACTIVITIES

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Formation flying and microspacecraft constellation missions pose new propulsion requirements. Formation flying spacecraft, due to the tight positioning and pointing control requirements, may need thrust control within 1- 20 μN to an accuracy of 0.1 μN for LISA and ST-7, for example. Future missions may have extended thrust ranges into the sub – mN range. However, all do require high specific impulses (>500 sec) due to long required thruster firings. Microspacecraft may need higher thrust levels into the sub – to low mN range, but may require small impulse bits well into the μNs range depending on mission, and need to be sufficiently miniaturized. At JPL, a variety of micro-thrust propulsion activities are being undertaken to address the various mission needs. These include evaluation of Indium FEEP and colloid thrusters for LISA and ST-7, test support for vacuum arc thruster development, novel micro-colloid thruster development, MEMS-based highly integrated micropropulsion systems for microspacecraft, as well as component development, such as microvalves and field emitter arrays for beam neutralization.

INTRODUCTION

Mission Background and Needs

There is an increasing need for micro-thrust propulsion devices in the aerospace community, able to deliver micro- to milli-Newton levels of thrust with thrust accuracies down to as little as 100 nN, and impulse bit capability down to 1 μNs or less. The need for this propulsion technology arises as new classes of missions are being developed and prepared for flight. Formation flying missions, such as Terrestrial Planet Finder (TPF), for example, are envisioned to employ interferometry to search for terrestrial planets around distant stars (see Fig. 1). Future missions may even search for the evidence of life on these planets and seek to image these planets (Life Finder, Planet Imager). Already, New Millennium ST-7, a pre-cursor to the joint European/US Laser Interferometer Space Antenna (LISA), is under design to demonstrate micro-thrust propulsion devices, such as colloid thrusters and Field Emission Electric Propulsion (FEEP) in space. LISA, which is envisioned to consist of a formation of three spacecraft (Fig. 2) will seek to detect gravity waves by means of laser interferometry as gravity waves pass through the formation and move its spacecraft with respect to each other.

Fig. 1: Terrestrial Planet Finder Mission Concept

Fig. 2: Laser Interferometer Space Antenna (LISA) Mission Concept

Such formation flying missions essentially represent a single, large interferometer instrument distributed amongst several spacecraft. This approach requires these spacecraft to be held in a precisely controlled formation, which in turn translates into a requirement for very small, low-noise thrust levels. Table 1 lists thrust, noise and impulse bit requirements for some of the formation flying missions currently under consideration. The table shows the very low required thrust and thrust noise levels in the 1-20 μN range and 0.1 μN range, respectively. At present, only a very limited number of propulsion devices appear able to meet these requirements, such as colloid, FEEP, and some other, novel micro-thrust devices, some of which will be reviewed in this paper.

Table 1: Some Formation Flying Requirements

Parameter	LISA/ST-7	TechSat 21	TPF
Thrust	1-20 μN	2 mN ('03) 40-200 μN (follow-on)	0.1 N (reformation) ~ μN (pointing)
Thrust Noise	0.1 μN		
Impulse Bit	-	2 mNs ('03) 2 μNs (follow-on)	

Another set of constellation missions also being studied increasingly is conducted mainly under NASA's Space Science Sun-Earth-Connection (SEC). There, each spacecraft features its own set of instruments, and relative positioning requirements may be relaxed in some cases. By using large constellations of dozens, perhaps up to a hundred spacecraft, tensor mapping of fields and particles may be conducted. The Magnetic Constellation (Mag Con) mission, for example, seeks to map Earth's magnetic field with 50 – 100 spacecraft (Fig. 3). Such large constellations of spacecraft are only feasible if very small spacecraft are used in order to keep total launch masses reasonable and launch cost affordable. So called "Nanosat" architectures are thus being envisioned, with total wet masses of 10 kg per spacecraft. Other examples of microspacecraft may be found in the defense area. The Department of Defense (DoD) has an interest in spacecraft constellations for Earth observation, ranging from 100-kg spacecraft in the TechSat 21 constellation (Fig. 4) to "picosats", i.e. 1 kg total wet mass spacecraft, studied by the Defense Advanced Research Projects Agency (DARPA) (Fig. 5).

In the case of such small spacecraft, significant propulsion system size and mass reduction is required for these subsystems to fit within the greatly reduced mass and size envelope. In addition thrust and impulse bit capabilities may also be required to be very small depending on spacecraft mass and required pointing accuracy. Table 2 lists potential impulse bit requirements and required thrust levels for slew (180°/min) for three generic cubical

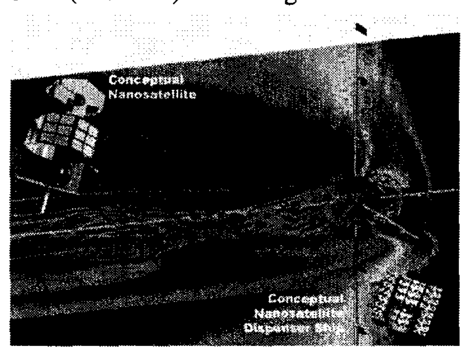

Fig. 3: Magnetic Constellation (MacCon) Mission Concept (Sun-Earth-Connection Theme)

Fig. 4: AF Tech Sat 21 Mission Concept

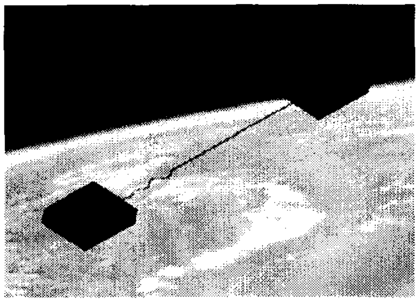

Fig. 5: DARPA 1-kg Picosat Spacecraft

spacecraft of 1, 10, and 20 kg mass, respectively[1]. Shown are different pointing (dead-band) requirements and time intervals between thruster firings. In general, longer time required between thruster firings (e.g. to not disturb measurements) requires lower rotation rates of the spacecraft as it drifts through the deadband, and, hence, a smaller impulse bits imparted onto the spacecraft is needed. As can be seen, required impulse bits may range from the mNs-range for larger craft having relatively coarse attitude requirements, into the μNs-range and possible even nNs range for very tight pointing requirements and very small spacecraft. On the other hand, slew rate requirements may drive required thrust levels into the milli-Newton range for 10-kg class spacecraft, while less than 0.1 mN maybe sufficient for 1-kg spacecraft. Note that these values are dependent on slew rate requirements, which may be relaxed to reduce thrust levels.

Micro-Thrust Propulsion Activities at JPL

A broad-based micro-thrust propulsion program has been built up at the Jet Propulsion laboratory (JPL) over the past several years to address the needs of formation flying, constellation, and microspacecraft missions that have emerged in the aerospace community. Activities include evaluation and development of micro-thrust devices for formation flight, as well as micropropulsion systems for microspacecraft.

Both categories of missions have slightly different needs. Formation flying requires very low thrust, low noise devices as outlined above. In addition, since these thrusters may be required to fire over long periods of time to offset constant solar pressure disturbances, high specific impulse (> 500 sec) is desired to reduce propellant requirements for the mission. In the case of microspacecraft, such as those envisioned for the SEC theme, very small mass and size of the propulsion system are of obvious importance, and thrust levels may actually be increased over those of formation flying missions, depending on the mass of the microspacecraft, and the mission and required slew rates.

There are, however, overlaps. For example, one might contemplate microfabricated colloid or FEEP thrusters, which deliver the required low thrust levels for formation flying missions, yet are micromachined to reduce mass of the overall system, allow for more largely distributed propulsion systems, and increase reliability due to increased redundancy, made affordable due to the small size of the thruster modules. Such a micro-colloid device is being studied at JPL, among others, and is reviewed below.

Similarly, microvalves may be used on small as well as large spacecraft, where flow rate requirements are low, such as in advanced electric propulsion feed systems perhaps. The program currently consists of several pillars of technology development and evaluation, focusing on these various mission needs, which will be outlined in the remainder of the paper. They include:

- Evaluation of existing micro-thrust propulsion technology for future interferometry formation flying and constellation missions. This technology includes Field Emission Electric Propulsion (FEEP) and colloid thrusters. Focus of this test bed activity is on performance verification, contamination and plume studies, and, eventually, life testing of industry-provided thruster hardware in order to aid mission designers, such as forST-7 and LISA, in the integration of these thruster technologies into their mission concepts and spacecraft
- Development of miniature-ion engine technology. This JPL in-house developed engine technology will provide thrust levels into the low milli-Newton thrust range at high (3000 sec) specific impulse values, suitable for constellation maneuvering in formation flying

Table 2: Representative Attitude Control Requirements for Microspacecraft

S/C Mass (kg)	S/C Typ. Dimension* (m)	Moment of Inertia (kg m^2)	Required Impulse Bit (Ns)						Minimum Thrust for Slew (mN)
			17 mrad (1°)		0.3 mrad (1 arcmin)		0.02 mrad (5 arcsec)		
			20 s	100 s	20 s	100 s	20 s	100 s	
1	0.1	0.017	1.4×10^{-4}	2.9×10^{-5}	2.5×10^{-6}	5.1×10^{-7}	1.7×10^{-7}	3.4×10^{-8}	0.06
10	0.3	0.150	4.3×10^{-4}	8.5×10^{-5}	7.5×10^{-6}	3.0×10^{-6}	1.0×10^{-6}	1.0×10^{-7}	1.75
20	0.4	0.533	1.1×10^{3}	2.3×10^{-4}	2.0×10^{-5}	4.0×10^{-6}	1.3×10^{-6}	2.7×10^{-7}	4.65

* Assume cubical spacecraft shape

applications, or attitude control of large inflatable spacecraft.

- Development of highly integrated micropropulsion systems including thrusters, valves and electronic driver circuitry by means of microfabrication. These devices are applicable to microspacecraft and the constellation missions in which they may be used.
- Development of key components needed in the realization of micro-thrust propulsion systems, such as field emission cathodes as cathodes and neutralizers in electric micro-thrust propulsion systems, and microvalves. Some of the valve design work is pursued jointly with industry.
- Establishment of first-rate facilities uniquely suited for micro-thrust propulsion evaluation and development. JPL has established state-of-the-art microfabrication facilities, a multitude of vacuum test facilities, a micro-Newton resolution thrust stand (originally developed by Princeton University), a field emitter cathode test facility, and most recently, is putting in place a Micropropulsion Design, Assembly, and Test (MPDAT) facility, consisting of 1000 sq ft Class 10 cleanroom space, equipped with a 2 m dia. Ultra-High Vacuum (UHV) chamber for FEEP and colloid propulsion evaluation, and to be used in a microspacecraft test bed.

This work is conducted out of JPL's Advanced Propulsion Technology Group, in close collaboration with other JPL internal institutions, such as the JPL Micro Devices Laboratory (MDL), the Center for Integrated Space Microsystems (CISM), and the Propulsion Flight Systems Group, as well as multiple outside institutions, such as (currently) Austrian Research Centers Seibersdorf, Busek Co., Inc., Alameda Sciences Inc., Moog Space Products Division, Vacco Industries, and Caltech. In the following sections, these various micro-thrust propulsion activities will be outlined in greater detail.

MICRO-THRUST PROPULSION FOR PRECISION FORMATION FLYING

Thruster Evaluation for LISA and ST-7

Future formation flying missions will have a need for micro-thrust propulsion, as outlined in the introduction. Two of the most near-term formation flying missions are the Laser Interferometry Space Antenna (LISA) mission, and its pre-cursor, the New Millennium ST-7 demonstrator, both developed jointly between NASA and the European Space Agency (ESA). ST-7 is a propulsion and instrument package, scheduled to fly onboard the European SMART-2 mission.

The LISA technology office has initiated micro-thrust propulsion evaluation through testing of an Austrian Indium-propelled FEEP thruster, built by Austrian Research Centers Seibersdorf (ARCS)[2,3] (Fig. 6). In this device, indium propellant heated into its liquid state is wicked up a very fine needle. This needle is placed opposite an extractor electrode featuring a circular hole concentric with the needle circumference. A high positive voltage applied to the needle (up to 10 kV) results in strong electric fields, amplified through the sharply pointed contour of the needle. Indium ions are torn from the liquid in a field emission process and accelerated in the field that created these ions.

Tests of an ARCS In-FEEP were conducted on a JPL micro-thrust stand with a resolution of about 0.5 μN or less to verify thrust data that previously had only been calculated based on other measured parameters, such as current and voltage[3]. The thruster tested was capable to deliver between 0.1 - 100 μN thrust. The thruster was subsequently tested with a thermionic cathode as well as cold cathodes serving to neutralize the positively charged ion beam[2]. The cold cathodes tested were of a carbon-nanotube type (by FEPET Inc.) and of a Spindt-type (SRI International)[2]. These tests were the first employing such cathodes in the beam neutralization of a FEEP thruster, and showed that these cathodes can be used to neutralize the beam. Future tests in a larger Ultra-High Vacuum (UHV) chamber currently under construction (see below) will be required and conducted under the LISA Technology program.

Most recently, NASA has selected a disturbance reduction control system as a pre-cursor to the LISA mission for the NASA ST-7 mission, to be flown on the ESA SMART-2 spacecraft. This disturbance reduction control system will employ a colloid thruster developed by Busek Co. of Massachusetts (Fig. 7). Busek colloid thrusters will be flown jointly with European micro-thrusters. JPL will support Busek in this flight project through neutralizer and contamination testing of the colloid thruster. The Busek thruster development is building on a previous development program at Busek under NASA New Millennium and Small Business Innovative Research (SBIR) programs. The thruster features an array of 57 stainless steel emitters with an ID of 30 μm. In this case, due to the propellant chosen (formamide or novel ionic liquids), charged liquid droplet, rather than ion, emission occurs. These droplets are

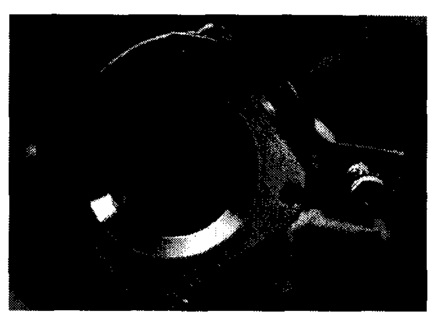

Fig. 6: ARCS In-FEEP Thruster with SRI FEA Cathode (Courtesy of Austrian Research Centers Seibersdorf and SRI International)

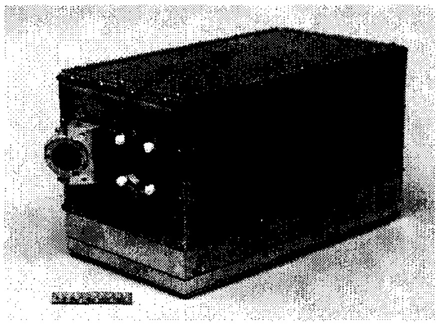

Fig. 7: Busek Colloid Thruster System (Prototype)
(Courtesy of Busek Inc.)

accelerated in the field between the emitter and an extractor that created these droplets, as well as a separate accelerator field.

The thruster is integrated with a zeolyte-based feed system that releases CO_2 from the zeolyte material upon heating to produce feed pressure on the propellant. A power conditioning unit providing the required voltages to the various system components completes the system. The system has demonstrated performances of 20 – 190 μN at about 6 W power consumption and 400 sec specific impulse in a Busek internal test program, to be fine-tuned to the desired thrust range of 1 – 20 μN and 500 sec Isp under the ST-7 program.

Miniature-Ion Engines

Xe-Bomdardment Thruster Technology

A 3-cm dia. miniature-ion engine was successfully built and tested at JPL under funding of the NASA Onboard Propulsion and Power CETDP[5-7]. This engine is a substantially scaled down version of conventional xenon electron bombardment ion thruster technology. Engines of this type, due to the use of benign xenon propellant, will not pose a contamination risk. The JPL miniature ion engine is conventionally machined, yet features novel, micromachined ion engine grids[5] (Fig. 8).

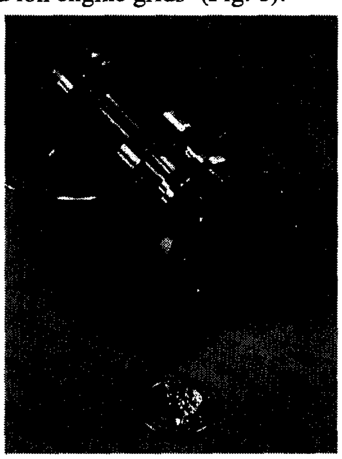

Fig. 8: Miniature-Ion Engine

These grids were manufactured by Vacco Industries Inc. of El Monte, CA though a proprietary chemical etching (ChEMS® - Chemical Etched Micro-Systems) technology. Various magnetic field configurations using miniature samarium cobalt permanent magnets were tested[6]. A hot-filament cathode was used in initial tests of the various engine configurations, later to be replaced by more efficient miniature hollow cathode, or cold cathode technology (see below)[6].

Typical performance data are summarized in Table 3. Also included in Table 3 is the so far highest engine efficiency data point. As can be seen, with one engine configuration using a divergent magnetic field and a small hole accelerator grid (SHAG) optics assembled from Vacco-micromachined grids, a maximum total engine efficiency of 56% was obtained at a thrust level of 1.5 mN and 28 mA beam current[7]. The SHAG optics increased propellant utilization to almost 80% and thus increased engine efficiency. It should be noted that thruster efficiencies were calculated excluding the power required for the hot-filament cathode. This is due to the fact that FEA cathodes are to be developed for this engine under this program. If FEA cathodes can be developed successfully to take the place of the hot filament, engine efficiencies would only drop slightly from he calculated values due to the low-power demand of FEAs.

In this context, it should also be noted that observed thruster efficiencies are quite high for an engine this size, where increased surface-to-volume ratios of the discharge chamber will lead to increased electron losses from the engine plasma to the wall surfaces. Measured values are now exceeding the performance goal of 50% efficiency. This has been achieved through magnetic field and ion engine grid (SHAG optics) optimization.

Table 3: Miniature Ion Engine Thruster Operation Ranges

Parameter	Typical Operating Range*	Best Efficiency Data Point*
V_B	700 – 1126 V	1089 V
V_D	23.5 – 29 V	25 V
V_A	200 – 230 V	218 V
J_B	7 – 29 mA	28.3 mA
J_D	70 – 550 mA	503 mA
J_A	0.5 –1.8 mA	0.906 mA
$\dot{m}_{prop}$	0.017 – 0.057 mg/s	0.050 mg/s
Power	14 – 50 W	43.39 W
P_{ch}	6.3E-6 – 2.0E-5 Torr	1.3 E-5 Torr
T	180 – 330°C	280°C
Thrust	0.4 – 1.56 mN	1.553 mN
I_{sp}	1764 – 3184 s	3184 s
ε_B	400 – 743 eV/ion	444 eV/ion
η_u	0.48 – 0.82	0.79
η_{tot}	0.31 – 0.56	0.56

*Values ignore doubly-charged ions and cathode input power.

The beam ion production cost in this maximum efficiency case was 444 ev/ion. Grid voltages of 1089 V screen and 218V accelerator voltage could be applied to the micomachined grids, resulting in (calculated) specific impulses comparable to those of conventional ion engines, i.e. 3184 sec. Power consumption in this case was about 50 W. Thrust values in general range between about 0.5 mN to 1.5 mN. depending on engine operating conditions at beam ion production costs of 400 – 743 eV/ion, power levels between 15-50 W, and beam currents between 7 and 29 mA. Propellant flow rates are between 0.017 – 0.057 mg/s xenon.

Vacuum Arc Thruster Technology (Alameda Applied Sciences Corp.)

A novel ion-thruster type is being developed by Alameda Applied Sciences Corp. of San Leandro, CA under funding of the NASA and USAF SBIR program and with testing support by JPL funded under the NASA Code R Advanced Propulsion Technology program[8,9]. This engine, termed the Vacuum Arc (Ion) Thruster, ablates small surface protrusions off any solid conductor (e.g. Titanium) propellant surface. This is achieved by applying a high voltage to the propellant surface and passing a current through the small surface protrusions. In the process, these protrusions heat up, and evaporate into a plasma cloud. The velocity of this plasma cloud is driven by pressure gradients and can reach values of up to 40,000m/s. This plasma may serve as an ion source in a vacuum arc ion thruster (VAIT) version, or be thermally expanded into vacuum in the vacuum arc thruster (VAT) version to produce thrust. Testing of the VAT on the micro Newton thrust stand at JPL indicated thrust to power ratios of $\approx 10\mu$N/W for Chromium, with thrust levels ranging as high as about 100 μN (Fig. 9).

The VAT was combined with an inductive energy storage power processing unit (PPU)[10] that can take 5-28VDC from the power bus and convert the energy stored in the inductor into a trigger pulse and a subsequent vacuum arc discharge. Measurements have shown PPU efficiencies of up to 90%. The PPU can be controlled remotely to adjust the thrust level over a wide range with constant efficiency. The PPU of the VAT is very versatile and can be used to drive multiple thruster heads. A thruster system has been developed for the ION (Illinois Observing NanoSat) mission[11] that can drive up to four individual thruster heads, allowing for individual control of each head by the onboard CPU and operating from a 12 V bus. The total PPU mass is 150g and the dimensions are 4cm x 4cm x 4cm (Fig. 10). New developments include a nano-Vacuum Arc Ion Thruster and a magnetically enhanced VAT for increasing the Isp.

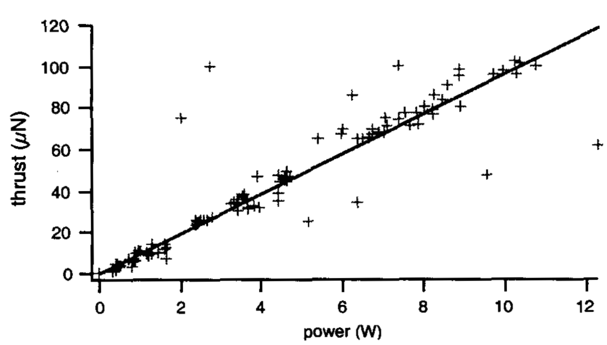

Fig. 9: Thrust-to-Power Ratios for a Cr VAT

Microfabricated Colloid Thruster

A novel activity to develop microfabricated colloid and FEEP thrusters is currently underway under discretionary funding from the JPL Directors Research and Development Fund (DRDF). This task studies the feasibility of fabricating colloid thrusters onto a silicon chip. Emitter openings even for conventionally machined thrusters are on the order of a few micrometer, which appears to make these thrusters amenable to on-chip miniaturization, thus realizing substantial mass and volume savings, yet still be applicable to large scale formation flying spacecraft. Using microfabrication techniques, many emitters may be machined simultaneously into the chip. These multi-emitter chips may be scaled to a wide range of desired thrust values, potentially exceeding those of much larger, conventionally machined devices. Microfabrciated devices may also make redundancy more affordable, increasing mission reliability. If successful, this thruster type would lend itself to high levels of integration, potentially featuring integrated field emission array (FEA) based neutralizers (see below) and tightly integrated propellant tanks and propellant feeds, allowing modular construction of micro-colloid or FEEP based propulsion systems with propulsion modules distributed over the spacecraft wherever needed.

Initial work is focusing on design and fabrication of microfabricated colloid chips, including wetting capabilities between propellant and various MEMS fabrication materials. The current design is a vertical emitter, featuring an array of 36, approx. 8 μm dia. Deep Reactive Ion etched (DRIE) capillary emitter holes. The length of the capillaries

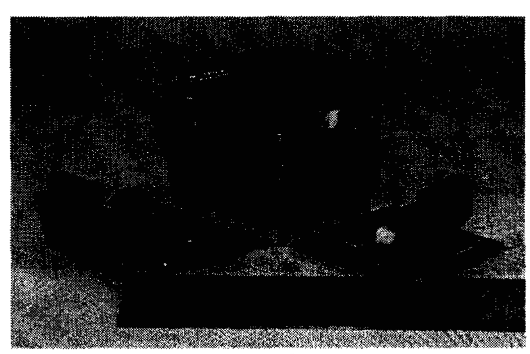
Fig. 10: VAT PPU for ION mission
(Courtesy of Alameda Applied Sciences Corp)

Fig.11: Emitter and Extractor Chips of a Microfabricated Colloid Thruster at JPL

is about 100 μm. The chip is fabricated from Silicon-on-Insulator (SOI) wafers to provide insulation to the extractor, which is separately machined, and made from silicon as well. A gold-thermal compression bond will be used to join it to the emitter chip. Emitter-extractor gap is designed to be 20 μm, with extractor grid holes varying between 40 and 200 μm in diameter. Ultimately, an accelerator chip will be bonded to the extractor chip, allowing further acceleration of emitted droplets to the desired exit velocities.

Micro-Component Development: Field Emitter Arrays

Electrostatic propulsion systems, such as ion engines, FEEP, or colloid thrusters discussed in this section, do require a neutralizer ejecting electrons in order to neutralize the positively charged ion beam emitted from the thruster. Micro-electric propulsion systems require this neutralizer to be miniaturized along with the thruster hardware, and be able to operate on low power levels. One option under consideration is that of Field Emitter Array (FEA) cathodes. In many of these cathodes, electrons are emitted via field emission processes from micromachined, very sharp, negatively biased micro-tips placed opposite a positively biased extractor grid[12-16]. Field emitter arrays have been developed extensively for flat panel arrays, where they operate in relatively benign vacuum environments of 10^{-7} Torr or so. For propulsion applications, these tips have to operate at pressures of 10^{-5} Torr or higher, and be subjected to eroding plasma ions, such as Xe^{+} or Xe^{++}.

JPL, in collaboration with SRI International, Linfield Research Institute, and FEPET Inc. is studying the applicability of various cathode types and materials to these propulsion plasma environments. Nanotube and microtip (Spindt-type) cathodes have been tested with an In-FEEP. Various sputter-resistant coating materials for Spindt-type cathodes are being investigated. JPL is developing a so called Cathode Lens and Ion Repeller (CLAIR) grid, to be micromachined and integrated with FEA structures to prevent potentially damaging plasma ions from reaching the microtips.

PROPULSION FOR MICROSPACECRAFT

Highly-Integrated Micropropulsion Systems

In addition to micro-thrust systems for formation flying missions, systems will be needed for microspacecraft constellations, such as Mag Con or picosat missions, which may require low, but slightly higher thrust levels than those needed for formation flying missions, very low impulse bits as described in the Introduction, and will need to be sufficiently miniaturized to match the small spacecraft envelopes. Micromachined, or MEMS propulsion devices are being studied to this end at various institutions around the world[1]. At JPL, a system consisting of a so called Vaporizing Liquid Micro-Thruster (VLM)[17-19], a Micro-Isolation Valve (MIV)[17,18,20-22] and a thruster/valve electronic driver chip is being developed. On key aspect of this development task is to achieve a tight integration between all these components to take full advantage of the mass and size benefits that MEMS-fabricated components do offer. This task is funded under the Micro/Nanospacecraft Cross Enterprise Technology Program (CETDP) task initially, and subsequently under the Enabling Concepts and Technology (ECT) element of NASA's Pioneering Research and Technology (PRT) Program.

The motivation for the integrated micropropulsion system approach is shown in Fig. 12. The top left portion of the figure shows a representative layout of conventionally integrated, state-of-the-art propulsion feed systems, consisting of conventionally machined, and relatively heavy and bulky components, assembled into a system via welded tube joints. Already available today are components, which, although employing conventional metal machining techniques, have achieved very high levels of miniaturization. For example, a state-of-the-art miniature cold gas thruster shown in the center part of Fig. 11 weighs as little as 7 grams[1]. Yet, these components still would have to be integrated into the overall system in a conventional fashion using welded tube joints, requiring additional space to facilitate the welding and assembly, which may far exceed the volume occupied by the individual components. MEMS components, were they to be packaged individually and assembled in a similar fashion, would not result in significant mass and volume savings over conventionally assembled propulsion systems using non-MEMS miniature components.

However, through on-chip integration, or 3-D chip stacking approaches, highly integrated propulsion modules may be envisioned, as shown in the lower right of Fig. 12. Integration of such tightly configured a MEMS propulsion module is not straightforward, and requires substantial efforts in the development of suitable packaging, assembly, interconnect, and thermal control approaches. At present, substantial progress has been made in the development of the individual components. The status of that work is summarized briefly below.

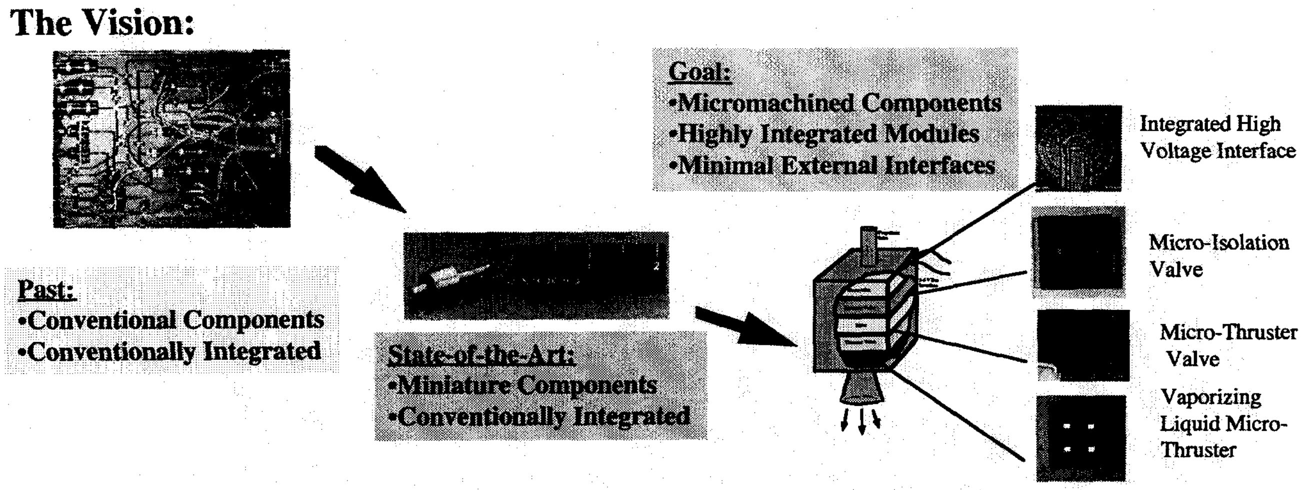

Fig. 12: Vision of Fully Integrated Microfabricated Propulsion Modules

The VLM is designed to serve as an attitude control thruster on microspacecraft. The most recent design is T-shaped to thermally isolate the heater section from the bulk of the chip (Fig. 13). It consists of a laminate of three chips[19] (Fig. 14). The two outermost layers contain thin-film deposited gold heaters, spaced apart by the third, center-chip. The chips are joined via a gold thermal compression bond, using a gold layer deposited in the same fabrication step as the heaters. Liquid propellant, in this case water for safety reasons, is pressure-fed between the heater strips, vaporized, and expanded through a micro-nozzle. The nozzle has a quasi-2-D conical (30° full angle) contour machined by Deep Reactive Ion Etching (DRIE) into the center chip together with the heater channel featured in the same chip. The two heater chips seal the channel and nozzle at the top and bottom. The chip ejects propellant sideways (see Fig. 14).

Several chips were tested on a micro-thrust stand. Recent tests yielded thrust levels of around 130 μN at a power level of about 1 W, corresponding to a thrust-to-power ratio of 130 μN/W (Fig. 15). This is considerably higher than thrust-to-power levels of other propulsion devices operating in this thrust regime, such as pulsed plasma thrusters or FEEPs. Improved packaging over earlier versions using a Pyrex stand-off to bond the VLM chip to a solenoid valve provided by the Lee company led to these results (see Fig. 16).

It should be noted that silicon, although the fabrication material of choice from a microfabrication point of view due to substantial MEMS heritage, is not the best material from the standpoint of thruster operation. This is because silicon is a very good heat conductor (about 150 W/m K), which leads to heat losses from the thrust chamber. Since novel MEMS fabrication techniques using more suitable materials are difficult and time-consuming to develop, insulation of

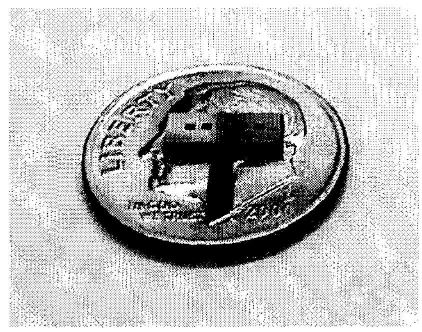

Fig.13: Vaporizing Liquid Micro-Thruster (VLM). (US Dime for scale)

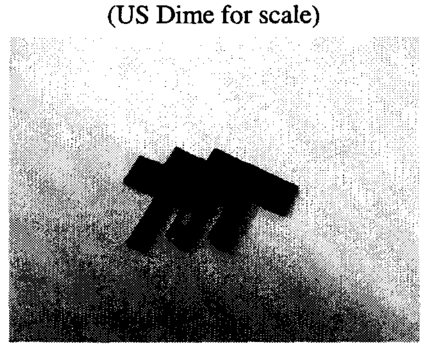

Fig. 14: VLM Thruster Chip Components. Observe nozzle contour on two left-most components.

the silicon chip was the approach chosen here. Note, however, that the set-up shown in Fig. 16 is merely a test rig to study VLM thruster chip behavior. Future packaging approaches will seek a more rugged and compact design.

Note the pulsating behavior in the thrust curve of Fig. 15 for these early test devices, which is typical for thrust curves generated by other devices at similar feed pressures. The reason for this is likely due to the low feed pressures of

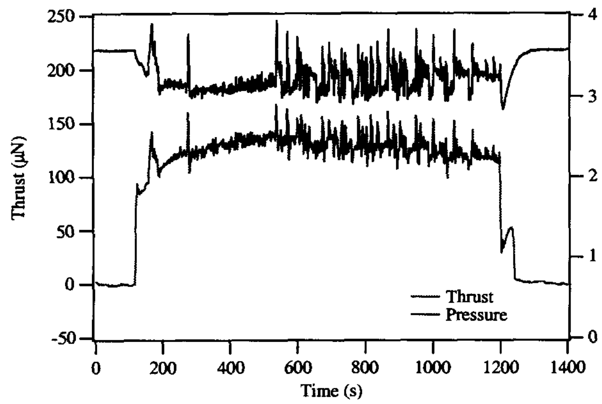

Fig. 15: 130-μN Thrust Curve and Feed Pressure for VLM

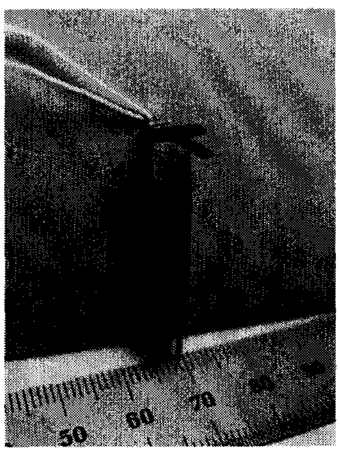

Fig. 16: Test Rig showing VLM chip attached to Solenoid Valve (Lee Inc.) via Pyrex Spacer featuring feed capillary.

1 – 4 psia used. With the current chip design, higher feed pressures would lead to flow rates too high for the chip to completely process the propellant into steam. Droplet ejection would result, which would decrease specific impulse and eventually would lead to formation of frozen propellant at the nozzle exit, as observed in some higher thrust cases than shown in Fig. 15 at the same 1 W power level. At lower feed pressures, vapor pressures inside the chip will be comparable to, or exceed these feed pressure, effectively causing flow blockage. It was noted in some of the test cases, that evaporation of propellant appeared to occur already in the upstream capillary inside the Pyrex stand-off due to the low pressures there. Future design iteration will seek to generate a higher pressure drop inside the thruster chip, permitting higher feed pressures. If feed pressures several times the vapor pressure inside the chip can be maintained, flow oscillation are expected to be damped out accordingly.

The MIV[15-17] will serve as an isolation valve in a similar function to a pyrovalve in conventional feed systems. It can only be opened once, and thus will not be able to serve in the function of a thruster valve. It may be required nonetheless depending on the nature of the mission in which microspacecraft may be used. Such craft may be placed onto larger spacecraft, for example, and be used as detachable probes for only a certain portion of the mission, such as inspection of another spacecraft, or a high-risk fly-by, such as past objects in Saturn's rings, or in a comets tail. In these cases, the microspacecraft may be dormant for long portions of the mission up to the point of its actual use. Given the expected low propellant quantity onboard a microspacecraft, extremely low, or zero leak rates will be required from the propulsion system up to that point. The MIV is designed to serve this function. Upon actuation of the microspacecraft, the MIV would be fired and the propellant system would be ready for use with its entire propellant quantity still available.

The MIV consists of two anodically bonded chips, one made from silicon and the other from Pyrex. The silicon chip features the flow channel. This channel is blocked by a silicon barrier, etched into place (see Fig. 17). An electric current is passed through the barrier, resistively heating and melting it. Thermal shock has also been observed to lead to cracking of the barrier. Debris of the barrier is trapped in debris traps and filters integrated into the chip. This valve was shown to have a burst pressure of up to 3000 psi (Fig. 18), and can be opened with capacitor-stored electrical energies of 10-60 mJ using driver capacitances of 0.6 - 16 μF depending on barrier thickness, ranging from 25 - 50 microns tested (Fig. 19). Recent experiments have shown successful debris trapping schemes, aimed at containing valve debris within the MIV chip to avoid contamination of downstream components. These experiments are ongoing.

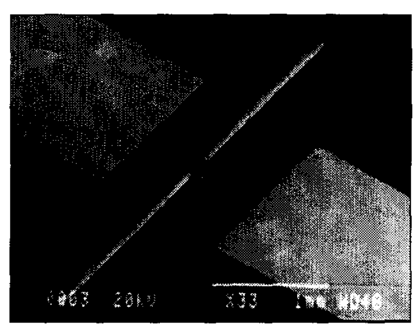
Fig. 17: Micro-Isolation Valve Flow Passage and Barrier

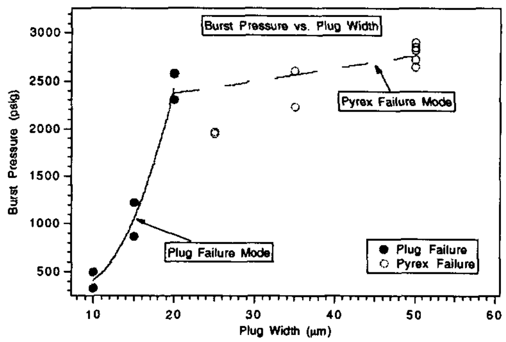

Fig. 18: MIV Burst Pressures[21]

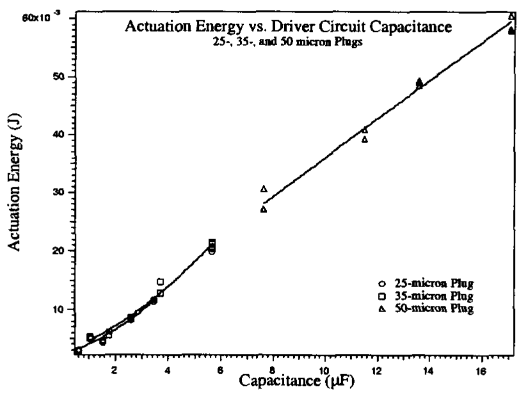

Fig. 19: Valve Actuation Energies and Driver Capacitances for various Plug Thicknesses[22]

A hybrid electronic driver chip is being fabricated to condition the electric power supplied to the VLM, MIV and a solenoid thruster valve (see below). Separate valve drivers for the VLM, MIV and the solenoid are located side-by-side on the driver chip. The VLM driver will determine the heater temperature by measuring the electric resistance of the heater strips and maintain a desired temperature by applying appropriate amounts of electrical power. The MIV driver will switch the stored electric energy of an external (off-chip) capacitor or inductor to the MIV chip upon command. The solenoid valve driver will drive a valve using power-consuming pulse width modulation (PWM) current pulses through the solenoid coil.

Micro-Component Development: Microvalves

In addition to the MIV development under the integrated micropropulsion systems task, microvalves that can be repeatable opened and closed and used as thruster valves are also being studied at JPL, partly in collaboration with industry. A micro-solenoid valve, termed the Moog Micro Valve (MMV), was developed in collaboration with Moog, Inc. Space Products Division under Moog IRAD and JPL DRDF funding[17] (see Fig. 20). This valve is 1 cm^3 in size and weighs 7 grams. At JPL, a three-dimensional microfabricated coil was under development to be used as actuator in this valve. The coil consists of a bonded wafer-

Fig. 20: Prototype Moog Micro Thruster Valve (MMV)

stack of individual spiral coils, electroplated into grooves of SU-8 photoresist, which in turn was deposited onto a silicon substrate. Coil development was taken to the individual wafer level, with electroplating procedures remaining to be worked out further[17]. In the meantime, a conventionally wire-wound coil manufactured by Moog was used as a placeholder to test valve performances. Table 4 shows a summary of valve performances[17]. A valve holding power of 0.7 W was determined. Opening time was 1.5 ms and closing time 0.5 ms. The valve was designed for an operating pressure of 300 psi, but was able to operate at up to 1000 psi. Leakage was < 10^{-4} sccs GN_2 after one million valve cycles.

A micro-piezo valve, that could fulfill a thruster valve function also, is being developed internally at JPL's Micro Devices Laboratory (MDL), previously under NASA

Table 4: Nominal Performance of 5 Prototype MMVs

Parameter	MMV Performance
Mass (gram)	7
Size (cm^3)	1 (approx. 1 x 1 x 1 cm)
Leakage (sccs GN_2)	< 10^{-4} (in all tests, during/after 10^6 cycles, 0 to 70°C)
Effective Flow Area (in.)	0.010 ESEOD (equivalent sharp edge orifice diameter)
Power, holding (W)	0.7 (continuous)
Bus Voltage (vdc)	5
Response, GN_2 (ms)	1.5 (open), 0.5 (close)
Pressure (psi)	300 (nom), 1000 (max)
Operating Temp (°C)	0-70**
Life	1,000,000 cycles*

*1 MMV tested. Test terminated voluntarily

** 1 MMV tested

Micro/Nano Spacecraft CETDP funding, and at present under NASA ECT funding (Fig. 21). This valve relies on a piezo-actuator that lifts a silicon armature of its valve seat to actuate the valve.

All silicon valve components are metal-to-metal compression bonded in a leak-proof, high-pressure tolerance metal packaging. The boss plate has a center plate with a 2 micron thick PECVD oxide layer, providing an initial seating pressure attributable to the tensile stress in the silicon tethers extended by the seat. A piezoelectric stack (block pressure 50 MPa) with mechanically separated active zones is bonded on top of the boss plate. Application of a potential (~40V) to the stack make the active zones vertically expand, lifting the boss center plate (bonded to the inactive zone of the stack) away from the seat plate (see Fig. 22). This action creates a channel between the two openings, allowing for the passage of fluids. The valve seat is unique in its design and consists of a series of very narrow (~ microns) concentric rings. It is envisioned that this seat design will allow contaminates to be trapped between the concentric rings rather than on the sealing surfaces, preventing complete closure of the valve. Multiple rings on the seat plate are designed to reduce potential leakage due to scratches over a seat ring.

Fabricated microvalves have been tested at upstream pressures of up to 1000 psi. Testing beyond 1000 psi has not been performed due to the safety limit of the current test setup. The leak test of a microvalve reveals an extremely low leak rate (9×10^{-5} sccm) at the pressure of 800 psi. The leak is undetectable at the pressures below 150 psi. Leak tests still have to be repeated after cycling. The flow rate of a microvalve, with 10 V applied, is 52 sccm at the inlet pressure of 300 psi. The power consumption of the microvalve, measured from the phase difference between the voltage from a signal generator and the current to a valve actuator, is 180 mW at 100 Hz.

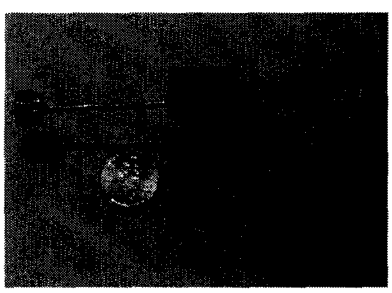

Fig. 21: Packaged JPL Micro-Piezovalve

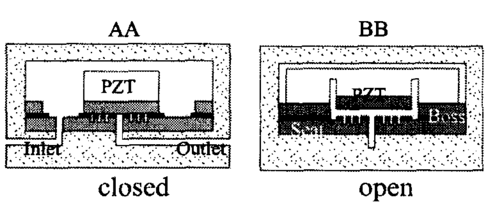

Fig. 22: Principle of Operation of JPL Micro-Piezovalve (Valve viewed from two directions, rotated 90°)

KEY FACILITIES

Micro- and Nano-Newton Thrust Stands

Measuring performances of the micro-thrust devices discussed in this paper requires extremely accurate thrust measurement capability. At JPL there exists a micro-Newton thrust stand with a resolution of 0.5 μN or better[3], and a Nano-Newton thrust stand with a resolution of 0.1 μN or better is currently under development. Both designs are based on thrust stand technology originally developed at Princeton University, which in turn was based on an earlier design by Fairchild[23].

The thruster is mounted onto a horizontally swing thrust arm, attached via two flexural springs at two pivot locations to a vertical support arm (see Fig. 23). The vertical arm in turn is attached to an L-shaped structure that can be leveled to eliminate gravity effects acting on the swinging thrust arm. The thrust arm deflects until the restoring force of the flexural springs and the thrust force equal. Thrust arm deflection can be measured via a Linear Variable Differential Transducer (LVDT) with a sub-micron resolution, resulting in about 0.5 μN thrust resolution. A damping circuit damps the natural oscillations of the thrust stand (typically with a 1- 10 s period) upon thrust actuation. Currently, a similar thrust stand design is underway, aiming to increase its resolution to 0.1 μN by using flexural springs with a lower spring constant. This will reduce the load carrying capability of the thrust arm, however, to approximately 2 kg from about 10 kg for the micro-Newton thrust stand.

Fig. 23: JPL Micro-Newton Thrust Stand (showing the ARCS Indium FEEP Thruster mounted to the right).

Micropropulsion Assembly, Design and Test (MPDAT) Facility

A novel Micropropulsion Design, Assembly and Test (MPDAT) facility is currently being constructed at JPL under JPL-internal Constructions-of-Facilities funding. This facility will consist of a large, 1000 sqft Class 10 cleanroom, placed into an existing building next to an existing Class 100 cleanroom (Fig. 24). This facility will provide a contamination-free environment for micropropulsion assembly, packaging, and testing, as well as a potential future microspacecraft testbed.

The first tests to be conducted in this facility will be in support of LISA and potentially ST-7, studying FEEP and potentially colloid thruster performances, plume behavior and neutralization, and contamination potentials. To this end, a large (2-m dia., 2-m long) Ultra-High Vacuum (UHV) chamber currently under construction will be placed into the MPDAT facility (Fig. 25). This UHV chamber will feature its own dedicated thrust stand, placed into a small side chamber that can be slid into the main chamber via a gate valve without breaking vacuum.

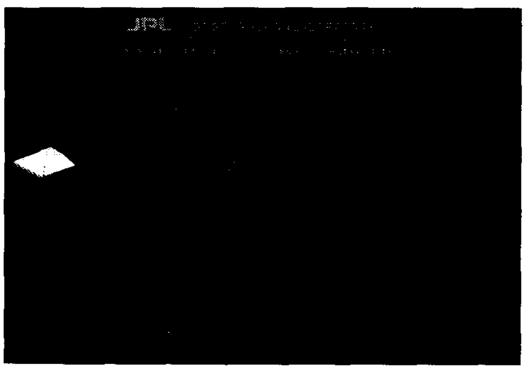

Fig. 24: JPL Micropropulsion Design, Assembly, and Test Facility (under construction)

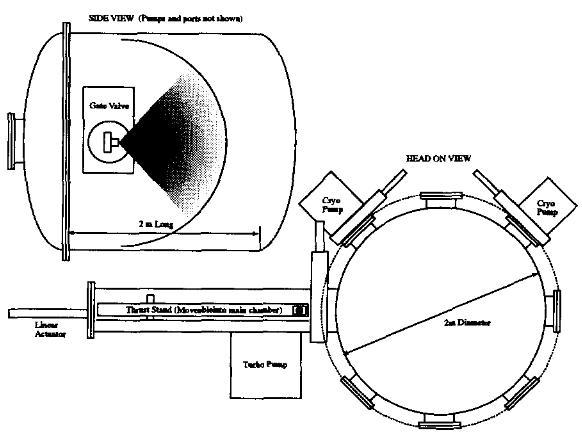

Fig. 25: Large 2-m dia. JPL UHV Chamber under construction for FEEP/Colloid Thruster Testing

Microdevices Laboratory

The Microdevices Laboratory (MDL) provides state-of-the-art facilities for a wide variety of semiconductor and micromachining processes that allow for end-to-end device development capabilities. MDL is a 38,000 square feet primary research and development facility with 12,000 square feet of cleanrooms and 6,000 square feet of diagnostic labs. MDL has a core set of equipment, including acid and solvent benches, evaporators, sputterers, dry etching machines, lithography, thin film testing machines, a Deep Reactive Ion Etcher for a very broad assortment of projects. It is uniquely dedicated to the R&D environment.

CONCLUSIONS

Formation flying and microspacecraft constellation missions pose new propulsion requirements. Formation flying spacecraft, due to the tight positioning and pointing control requirements, may need thrust control within 1- 20 μN to an accuracy of 0.1 μN for LISA and ST-7, for example. Future missions may have extended thrust ranges into the sub – mN range. However, all do require high specific impulses (>500 sec) due to long required thruster firings. Micropsacecraft may need higher thrust levels into the sub – to low mN range, but may require small impulse bits well into the μNs range depending on mission, and need to be sufficiently miniaturized.

At JPL, a variety of micro-thrust propulsion activities are being undertaken to address the various mission needs. These include test bed evaluations of FEEP and colloid thrusters for LISA and ST-7, novel microfabricated colloid thrusters, test evaluation of vacuum arc thrusters, integrated micropropulsion schemes for microspacecraft, and various component development technologies, including microvalves and field emitter arrays.

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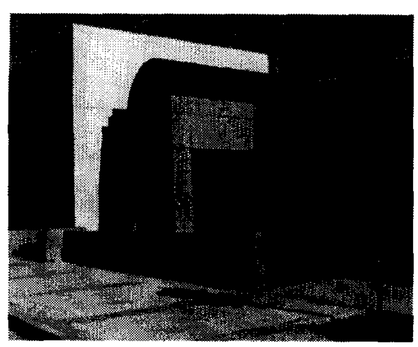

Fig. 25: JPL Microdevices Laboratory (MDL)

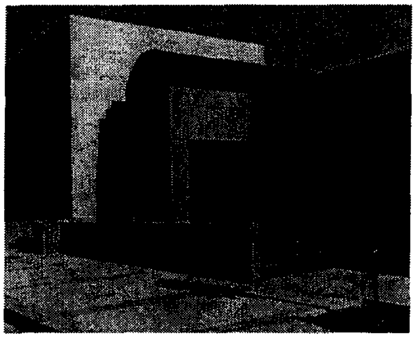

Fig. 27: JPL Microdevices Laboratory (MDL)

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REFERENCES

[1]Mueller, J., "Thruster Options for Microspacecraft: A Review and Evaluation of State-of-the-Art and Emerging Technologies", *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 3.

[2]Marrese-Reading, C., Polk, J, Mueller, J., Owens, A., Tajmar, M., Spindt, C., and Fink, R., "In-FEEP Thruster Ion Beam Neutralization with Thermionic and Field Emission Cathodes", IEPC Paper 01-290, International Electric Propulsion Conference, Oct. 15-19, 2001, Pasadena, CA.

[3]Ziemer, J., "Performance Measurements Using a Sub-Micronewton Resolution Thrust Stand", IEPC Paper 01-238, International Electric Propulsion Conference, Oct. 15-19, 2001, Pasadena, CA.

[4]Hruby, V., Gamero-Castaño, Falkos, P., and Shenoy, S., "Micro-Newton Colloid Thruster System Development", IEPC Paper 01-281, 27th International Electric Propulsion Conference, Oct. 15-19, 2001, Pasadena, CA.

[5]Mueller, J., Marrese, C., Wang, J., and Polk, J., "Design and Fabrication of a Micro-Ion Engine", AIAA Paper 2000-3264, 36th Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000.

[6]Wirz, R., Escobado, J., Sheehan, P., Polk, J., Marrese, C., and Mueller, J., "Development and Testing of a 3-cm Electron Bombardment Micro-Ion Thruster", IEPC Paper 01-343, International Electric Propulsion Conference, Oct. 15-19, 2001, Pasadena, CA.

[7]Wirz, R., Polk, J., Marrese, C., and Mueller, J., "Experimental and Computational Investigation of the Performance of a Micro-Ion Thruster", AIAA Paper 2002-3835, 38th Joint Propulsion Conference, July 7-10, 2002, Indianapolis, IN.

[8]Schein, J., Qi, N., Binder, R., Krishnan, M., Ziemer, J., Polk, J., and Anders, A., "Low Mass Vacuum Arc Thruster System for Station Keeping Missions", IEPC Paper 01-228, International Electric Propulsion Conference, Oct. 15-19, 2001, Pasadena, CA.

[9]Qi, N., Schein, J., Binder, R., Krishnan, M., Anders, A., and Polk, J., "Compact Vacuum Arc Micro-Thruster for Small Satellite Systems", AIAA Paper 2001-3793, 37th Joint Propulsion Conference, July 8-11, 2001, Salt Lake City, UT.

[10]Schein, J. , Qi, N., Binder, R., Kishnan, M., Ziemer, J., Polk, J., and Anders, A. "Inductive Energy Storage Driven Vacuum Arc Thruster", Rev. Sc. Instr 73(2), 2002, pp. 925-927.

[11]Rysanek, F. , Hartmann, J.W., Schein, J., and Binder, R., "MicroVacuum Arc Thruster Design for a CubeSat Class Satellite", Paper SSC02-I-2, 16th Small Satellite Conference, Aug. 12-15, 2002, Logan, UT.

[12]Marrese-Reading, C., Polk, J., and Jensen, K., "Experimental Performance Evaluations of Mo and ZrC-Coated Mo Field Emission Array Cathodes in Oxygen Environment", IEPC Paper 01-278, International Electric Propulsion Conference, Oct. 15-19, 2001, Pasadena, CA.

[13]Marrese, C., Polk, J., Jensen, K., Gallimore, A., Spindt, C., Fink, R., and Palmer, W., "Performance of Field Emission Cathodes in Xenon Electric Propulsion System Environments", *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA, Reston, VA, 2000, Chap. 11.

[14]Marrese, C. and Wang, J., "Space-Charge-Limited Emission from Field Emission Cathodes for Electric Propulsion and Tether Applications", *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 18.

[15]Marrese, C. and Polk, J.., "Molybdenum Field Emission Array Cathode Performance in Primarily Xenon Environments: Preliminary Experimental Results at Low Operating Voltages", AIAA Paper 2000-3266, Joint Propulsion Conference, July 16-19, 2000, Huntsville, Al.

[16]Marrese, C., Gallimore, A., Polk, J., Goodfellow, K., and Jensen, K., "Field Emission Cathodes for Electric Propulsion Systems", AIAA Paper 98-3484, Joint Propulsion Conference, 1998, Cleveland, OH.

[17]Mueller, J., Yang, E.H., Green, A., White, V., Chakraborty, I., and Reinicke, R., "Design and Fabrication of MEMS-Based Micropropulsion Devices at JPL", Invited Paper, in "Reliability, Testing, and Characterization of MEMS/MOEMS", edited by Ramesham, R., Proceedings of SPIE Vol. 4558 (2001), pp. 57-71.

[18]Mueller, J., Marrese, C., Polk, J., Yang, E.H., Green, A., White, V., Bame, D., Chakraborty, I.,, and Vargo, S., "An Overview of MEMS-Based Micropropulsion Developments at JPL", Paper IAA-B3-1004, Presented at the 3rd International Symposium of the International Academy of Astronautics (IAA) for Small Satellites for Earth Observation, Berlin, Germany, April 2-6, 2001.

[19]Mueller, J., Chakraborty, I., Bame, D., and Tang, W., "The Vaporizing Liquid Micro-Thruster Concept: Preliminary Results of Initial Feasibility Studies", *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 8.

[20]Mueller, J., Vargo, S., Green, A., Bame, D., Orens, R., and Roe, L., "Development of a Micro-Isolation Valve: Minimum Energy Requirements, Repeatability of Valve Actuation, and Preliminary Studies of Debris Generation", AIAA Paper 2000-3675, 36th Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000.

[21]Mueller, J., Vargo, S., Bame, D., Chakraborty, I., and Tang, W., "The Micro-Isolation Valve Concept: Initial Results of a Feasibility Study", *Micropropulsion for Small Spacecraft*, Progress in Astronautics and Aeronautics, Vol. 187, edited by Micci, M. and Ketsdever, A., AIAA , Reston, VA, 2000, Chap. 17.

[22]Mueller, J., Vargo, S., Chakraborty, I., Forgrave, J., Bame, D., and Tang, W., "The Micro-Isolation Valve: Introduction of Concept and Preliminary Results", AIAA Paper 98-3811, 34th Joint Propulsion Conference, Cleveland, OH, July 13-15, 1998.

[23]Parker, J.M., Thunnissen, D., Blandino, J., Ganapathi, G., "The Preliminary Design and Status of a Hydrazine Milli-Netwon Thruster development", AIAA Paper 99-2596, 35th Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999.

[24]Cubbin, E., Ziemer, J., Choueiri, E., and Jahn, R., "Pulsed thrust measurements using laser interferometry", Rev. Sci. Instrum. 68 (6), June 1997, pp. 2339 – 2346.